A RELIABLE GAIN EXPANDER FOR SEISMOGRAPH AMPLIFIERS

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PREFACE

This thesis has as its purpose a description of a new method for reliably controlling the gain of a seismograph amplifier. This gain control is of the expander type and causes the gain or sensitivity of the amplifier to increase predictably as a function of time after a specified instant.

This method of gain control is particularly useful in two applications. (1) Its accuracy is important in the field of basic research when the strength of a seismic signal is to be measured, and (2) it is also particularly useful when recording seismic signals on magnetic tape where full fidelity must be maintained. This is because any automatic means of gain adjustment is apt to distort low frequency signals.

In order to be useful as a field circuit, it must satisfy stringent requirements with regards to reliability, freedom from vacuum tube selection, ease of maintenance, and precision. The unit described herein has been in use several years and has met these requirements.

The circuitry described in this paper was designed, built, and tested by the author in connection with a research project conducted in the Research Center of the Stanolind Oil and Gas Company, Tulsa, Oklahoma. The Research Center is managed by Mr. George Roberts, Jr., and the Exploration Research Division director is Dr. Daniel Silverman.

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CHAPTER ONE

INTRODUCTION

Oil is found in the pores of rocks in the earth. Salt water also is found in these rock pores. Since the oil is lighter than the salt water, it floats on the salt water and moves upward to a fold or dome in the rock where it accumulates under an impervious hard rock layer. Where rocks are bent upward at the surface, geologists map the surface features to find locations for drilling prospective oil wells. Where surface geology is inadequate, the underlying domes or folds are most often discovered by means of seismograph instruments.

Seismograph instruments are normally used for recording earth tremors caused by earthquakes. When they are used to locate geological structures, an artificial earthquake is used to generate the earth tremors. A dynamite charge is detonated in a shot hole. This explosion causes a minute earthquake. The seismic waves, or vibrations, of this earthquake travel down through the earth until they reach an interface between two layers of different elastic properties. Then they are reflected back to the surface of the earth. Sound detectors (seismometers) on the surface pick up the reflected vibrations and convert them into electrical waves. These electrical signals are transmitted to a recording truck by means of wires. In the recording truck is a special seismograph which is suitable for recording the particular type of vibrations caused by the miniature earthquake. The waves are recorded on an oscillographic record which has very precise timing marks placed on it. By timing the reflected waves, the depth to the strata from which they were reflected can be calculated. By repeating this process in an area, a map of the subsurface strata can be made and underlying domes or folds can be located.

In general, the amplitude of the waves received from interfaces close to the earth's surface is much greater than the amplitude of the waves received from interfaces at greater depths. A wave reflected from a shallow interface is received earlier and is of greater amplitude than a wave reflected from a deep interface. If the sensitivity of the recording system and the size of the dynamite charge are so adjusted as to record the reflected waves from a deep interface with the desired amplitude, then the amplitude of reflected waves from shallower interfaces will be so great that the characteristics are not readily observable from the record produced. In general, it may be said that the amplitude of the various waves received is approximately inversely proportional to the distance they have traveled through the earth. The velocity of travel through the various strata is not exactly the same. Hence, the amplitude of the waves received is only approximately in inverse proportion to their travel time from the shot point to the recording point.

In modern seismograph amplifier equipment, provision is made for automatically adjusting the gain of the amplifier so that the signal to be recorded on the oscillograph is approximately constant. This is accomplished by means of an automatic gain control (agc) circuit which senses the output level of the amplifier and adjusts the gain accordingly. At the beginning of the seismograph record, the signal level from the seismometers is high and the agc circuit reduces the gain of the amplifier, so as to produce a readable amplitude on the record. As time progresses, the waves from the seismometer become weaker. The agc senses this and increases the gain by an appropriate amount. This agc action produces a seismograph record which has approximately the same recording level throughout its length although the amplitude of the seismic waves may vary by a factor of as much as 4000 to 1 from the beginning of the record to the end.

Although an agc seismograph amplifier produces a readable record, it can also produce some undesirable results. For example, one of the information parameters of the seismograph signals is thrown away. This is its amplitude characteristic. To those familiar with the art of interpreting seismograph records, the amplitude, or at least the relative amplitude of succeeding waves, can be of some importance. The agc circuit, if it is to be quick enough acting to produce a readable record, destroys most of this amplitude information. Since the agc system controls the gain of the amplifier in accordance with the average signal level, its action is not instantaneous. Its action on a large signal followed closely by a small signal will cause the gain of the amplifier to be reduced to such a point that the small signal may not be recorded at an amplitude sufficiently large to be observed. Hence, agc circuits are undesirable for use when such conditions exist.

A recent innovation in the art of seismic exploration is the use of magnetic recorders. The seismic signal is recorded on magnetic tape instead of on an oscillographic record. The magnetic tape is then taken to a field office or laboratory where it is played back through special analyzing equipment. This method offers several advantages in that the signal can be reanalyzed whenever desired. As new methods are developed for better recovering the desired seismic information, they may be tried without the necessity of returning to the field to obtain the data. The seismic signal to be recorded may contain signals which are very low in frequency. An agc circuit which is quick acting will alter the character or frequency spectrum of these waves since their period may be approximately the same as the speed of action of the agc circuit. For this reason, agc circuits are not always desirable for use when recording seismic signals magnetically.

In some basic research work on seismograph signals, it is necessary to measure the absolute amplitude of the signals, and the agc method of recording is unsatisfactory since the amplitude information is obliterated. It was primarily for this reason that the gain expander described in this thesis was developed.

A gain expander for a seismograph amplifier is a device which automatically causes the gain of the amplifier to increase as a function of time after the time of detonation of the dynamite charge. The maximum and minimum values of gain as well as the rate of increase of the gain can be adjusted so that all the received waves are recorded with their amplitudes sufficiently alike to afford satisfactory observation of all the waves on the oscillograph record. In some cases it is desirable to have the system designed so that the gain automatically increases after the instant the first direct wave arrives at the recording position. However, this particular feature is well known to those in the seismograph field and will not be discussed further.

Several types of gain expanders have been developed for seismograph systems, one of the earliest being described by Mr. W. T. Born[1], in which the bias on a variable-mu vacuum tube is varied, causing the voltage amplification of the stage to vary. The bias voltage is derived from a charged condenser which is discharged through a resister during the expansion period. This system has a serious disadvantage in that the variable-mu characteristics of vacuum tubes are neither stable nor alike between various tubes. Before the advent of satisfactory agc circuitry, this type of gain control was widely used in the industry. Because of its instability, added to the difficulty of the requirement that the operator anticipate the intensity and decay rate of the seismic signals, it was superseded by the agc circuits. The latter difficulty is still present with the reliable gain expander described herein. It is minimized by the fact that one of the factors of variability is removed, and provides a system which is satisfactorily operable.

The principle upon which this gain expander is designed is based on the exponential portion of the plate-voltage/plate-current characteristic of a thermionic diode. This exponential portion of the diode characteristic

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[1] U. S. Patent No. 2,324,816, W. T. Born, July 20, 1943.

occurs at plate voltages more negative than those for which the three halves power holds. This exponential relationship is classical[2] and is important both theoretically and practically because it is essentially independent of variations in tube construction and processing and therefore gives accurately reproducible results that do not demand careful selection of tubes.

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[2] W. R. Ferris, "Some Characteristics of Diodes with Oxide-Coated Cathodes", <u>RCA Review</u>

CHAPTER TWO

CIRCUIT THEORY

The description of the reliable gain expander for seismograph amplifiers will be separated into four parts. The first part will describe how the dynamic resistance of a thermionic diode varies as a function of the plate current. The second part shows how this characteristic is utilized in the basic attenuation circuit. The third part describes the circuitry which controls the basic attenuation circuit. The fourth part develops the attenuation formula based on the control circuitry provided.

DYNAMIC RESISTANCE OF A THERMIONIC DIODE

There are three clearly distinguishable conditions of current flow from the cathode to the anode of a thermionic diode. When a large positive voltage is applied to the anode, relative to the cathode, substantially all of the emitted electrons are drawn to the anode, and the current is a "saturation" current. For a range of lesser positive anode voltages, the current is governed by the space charge conditions surrounding the cathode and is proportional to approximately the 3/2 power of the applied voltage. For a range of very small positive, zero, and small negative voltages, the factor regulating the magnitude of the current from the cathode to the anode is the initial velocity of the electrons given off by the thermionic cathode.

In the circuitry to be described, the diodes are always operated in this last region, where the slope of the cathode-anode voltage-current characteristic is determined by the electron initial velocities. This condition of operation will be referred to as in the "electron initial velocity" region. In this region, the current through a thermionic diode is given by the formula[3]:

$$I = I_s \frac{2}{\pi} \sqrt{\frac{eV}{kT}}\, \epsilon^{\frac{-eV}{kT}} \qquad (1)$$

where

I = d-c diode current

I_s = saturation current

e = electron charge

V = plate-cathode voltage

k = Boltzmann's constant

T = temperature, absolute

ϵ = 2.71828

Since I_s is constant for any given temperature T, taking the logarithms of both sides of this equation gives:

$$\ln I = A + \ln \sqrt{\frac{eV}{kT}} - \frac{eV}{kT} \qquad (2)$$

where

$A = \ln \frac{2 I_s}{\sqrt{\pi}}$, a constant.

In this expression the term:

$$\ln \sqrt{\frac{eV}{kT}} \ll \frac{eV}{kT}$$

---

[3]Harnwell and Livingood, "Experimental Atomic Physics", p. 202

Then Equation 2 becomes:

$$\ln I = A - BV \tag{3}$$

where

$$B = \frac{e}{kT}$$

Plotting log I against the voltage V in the region of interest yields a straight line of slope

$$-.4343 \frac{e}{kT}$$

The dynamic resistance of the diode from (3) is given by:

$$r_p = \frac{dV}{dI} = \frac{-1}{B} \cdot \frac{1}{I} = \frac{C}{I} \tag{4}$$

where

$$C = -\frac{1}{B}$$

Thus, it appears that the dynamic resistance r_p is a function of substantially only I and B. B is inversely proportional to T and, since it is not difficult to maintain T relatively constant, then the dynamic resistance is a function only of the current I. Thus, we have a control element which can be used as a variable resistance in an attenuating network and the resistance can be quite accurately predicted for specific values of I. It should be noted at this point, however, that the voltage characteristic of various diodes may be shifted considerably with respect to each other, and that to accurately predict the dynamic resistance of a diode, the current must be accurately controlled in the face of the change in voltage characteristic. Plate voltage vs. plate current voltage characteristics of several test diodes are shown in Figure 1.

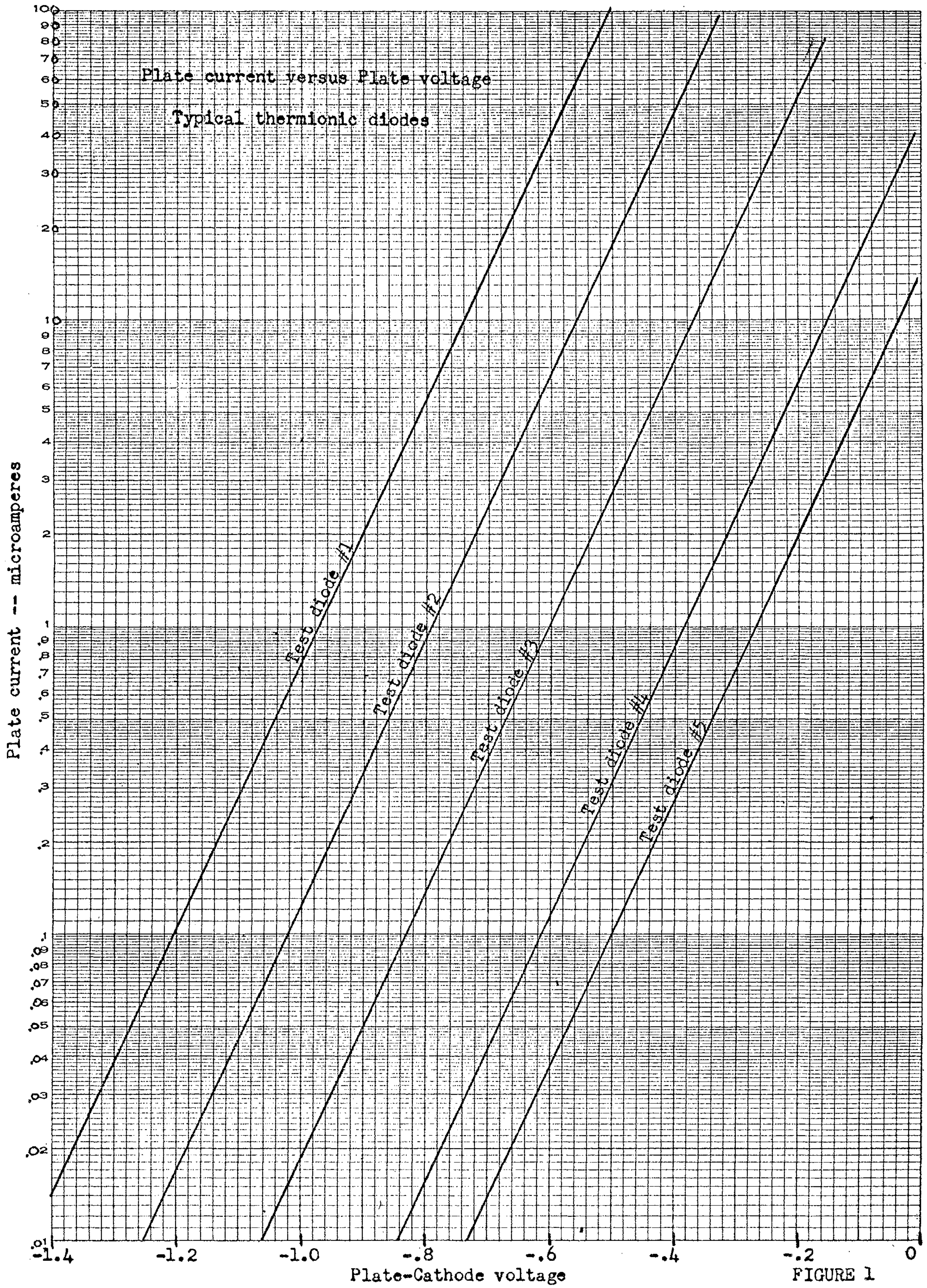
Plate current versus Plate voltage
Typical thermionic diodes
Test diode #1
Test diode #2
Test diode #3
Test diode #4
Test diode #5
Plate current -- microamperes
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
-1.4
-1.2
-1.0
-.8
-.6
-.4
-.2
0
Plate-Cathode voltage

FIGURE 1

BASIC ATTENUATION CIRCUIT

Normally, seismic amplifiers are of the unbalanced type, i.e., the signal circuit is referenced to ground. For this reason, it is undesirable to utilize a single diode in the attenuating circuit, because the control voltage used to vary its resistance would be introduced into the circuit and create undesirable transients in the signal path.

In this attenuation circuit, the diodes are arranged in an L-pad attenuator shown in Figure 2a. This basic circuit is widely used in seismic amplifiers having agc[4]. The equivalent circuit is shown in in Figure 2b. The operation of this circuit is as follows: When E_c is high and of such a polarity that B is negative with respect to A, then an infinitesimal amount of current flows through the diodes and their resistance is very high compared to R. Under these condition, the circuit has virtually no attenuation to the signal. When E_c is of such a value and polarity to cause current I to flow, then the current through both diodes is identical due to the capacitors C_1 and C_2 in the circuit. These capacitors are large enough to effectively provide negligible reactance to the signal frequencies, and are provided to assure that the sole path of the current I is through the diodes. The resistance of each of the diodes is identical and from (4) is equal to C/I. Hence, we have an attenuator circuit in which

$$\frac{E_{out}}{E_{in}} = \frac{r_D}{r_D + R} = \frac{1}{1 + \frac{R}{r_D}} \qquad (5)$$

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[4]U. S. Patent No. 2,663,002, L. B. McManis et al, Dec. 15, 1953

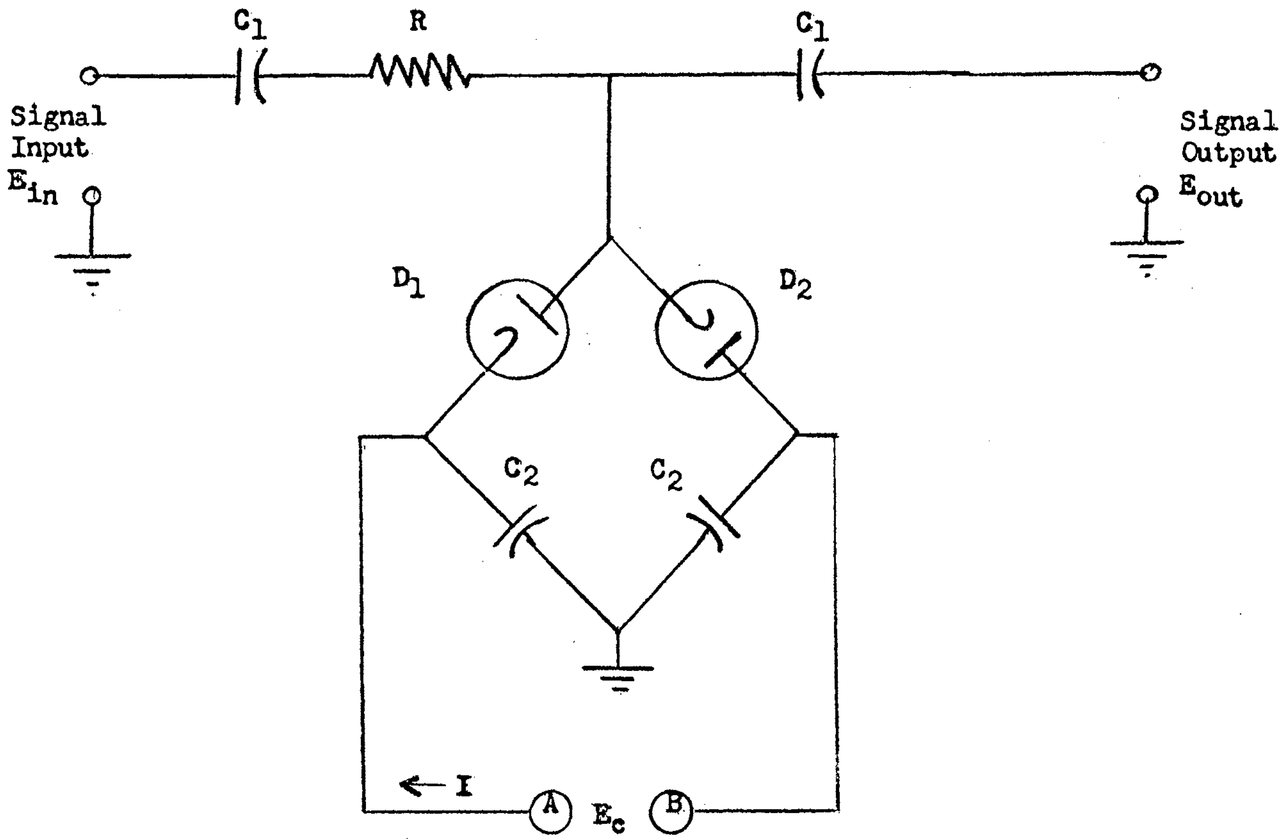

FIGURE 2A

BASIC ATTENUATION CIRCUIT

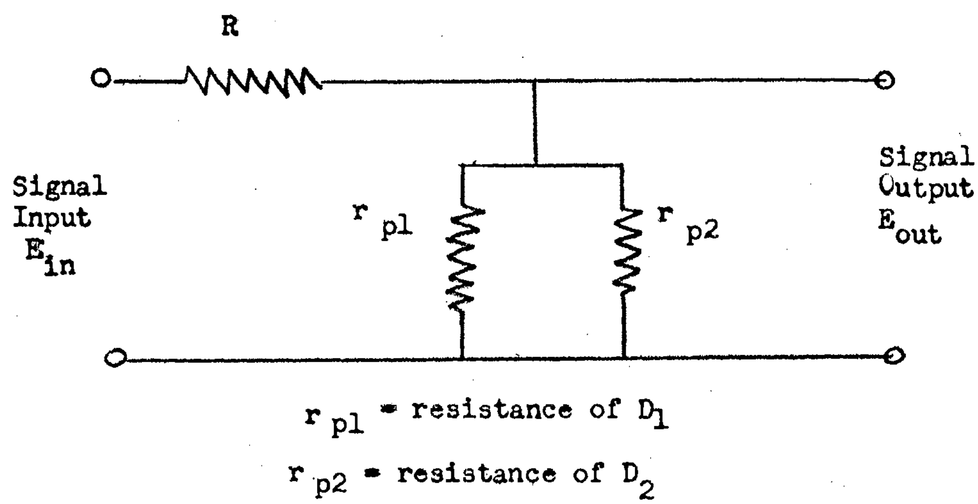

FIGURE 2B

EQUIVALENT BASIC ATTENUATION CIRCUIT

where

$$r_p = \frac{r_{p1}}{2} = \frac{r_{p2}}{2}$$

The attenuation of the circuit expressed in decibels (db) is

$$\begin{aligned} \text{Att(db)} &= 20 \log \frac{E_{in}}{E_{out}} \\ &= 20 \log \left(1 + \frac{R}{r_p}\right) \end{aligned} \qquad (6)$$

The shunt arm of this attenuator consists of the thermionic diodes and the capacitors C_2 arranged in a bridge circuit. This is for the purpose of preventing any of the control voltage (E_c) transients from entering the signal path. This assumes, of course, that the two capacitors C_2 are identical and that the incremental resistances of the diodes D1 and D2 are also identical. The two capacitors C_2 can be selected to be equal. As previously mentioned, the current through the two diodes are identical, and hence their plate resistances are identical. This does not imply that the d-c potential existing at the junction of the two diodes will be zero. Reference to Figure 1 will reveal that various diodes generally will have different plate-cathode potentials at the same plate currents. However, the <u>incremental</u> change in plate voltage versus plate current is identical. This is readily seen from the graph and from (4). Thus, there will at all times exist a static potential at the junction of the diodes which is dependent upon the particular diodes selected, but this potential will remain constant regardless of the value of E_c. Hence, any changes in E_c will not be introduced into the signal circuit as long as the capacitors C_2 are equal and the diodes have the same temperature.

CONTROL CIRCUITRY FOR BASIC ATTENUATION CIRCUIT

The function of the attenuator circuit is twofold. First, it must attenuate at a specified value so that at the beginning of the seismograph record, when the first large amplitude signals are received, the signal will have a readable amplitude. This is defined as "initial attenuation". Second, it must reduce the attenuation at a controlled rate as the succeeding seismic signals coming from deeper beds become weaker. The rate of travel of seismic waves through the earth is variable, depending on the area, and the attenuation of the various beds through which the seismic waves travel is also variable, depending on the acoustic properties of the different geological strata. Hence, the rate of attenuation reduction must be controllable. In a particular geological region, the rate of attenuation reduction required is consistent, so the circuit must provide this rate reliably. The rate of attenuation reduction is referred to as the "expansion rate".

The circuitry by which the initial attenuation and expansion rate is accurately controlled is shown in Figure 3. This is basically the same circuit as shown in Figure 2a except that the control voltage E_c has been replaced by suitable networks to provide the needed functional operation.

The initial attenuation condition is attained when switch S_1 is closed and switch S_2 is open. The current through the diodes is then

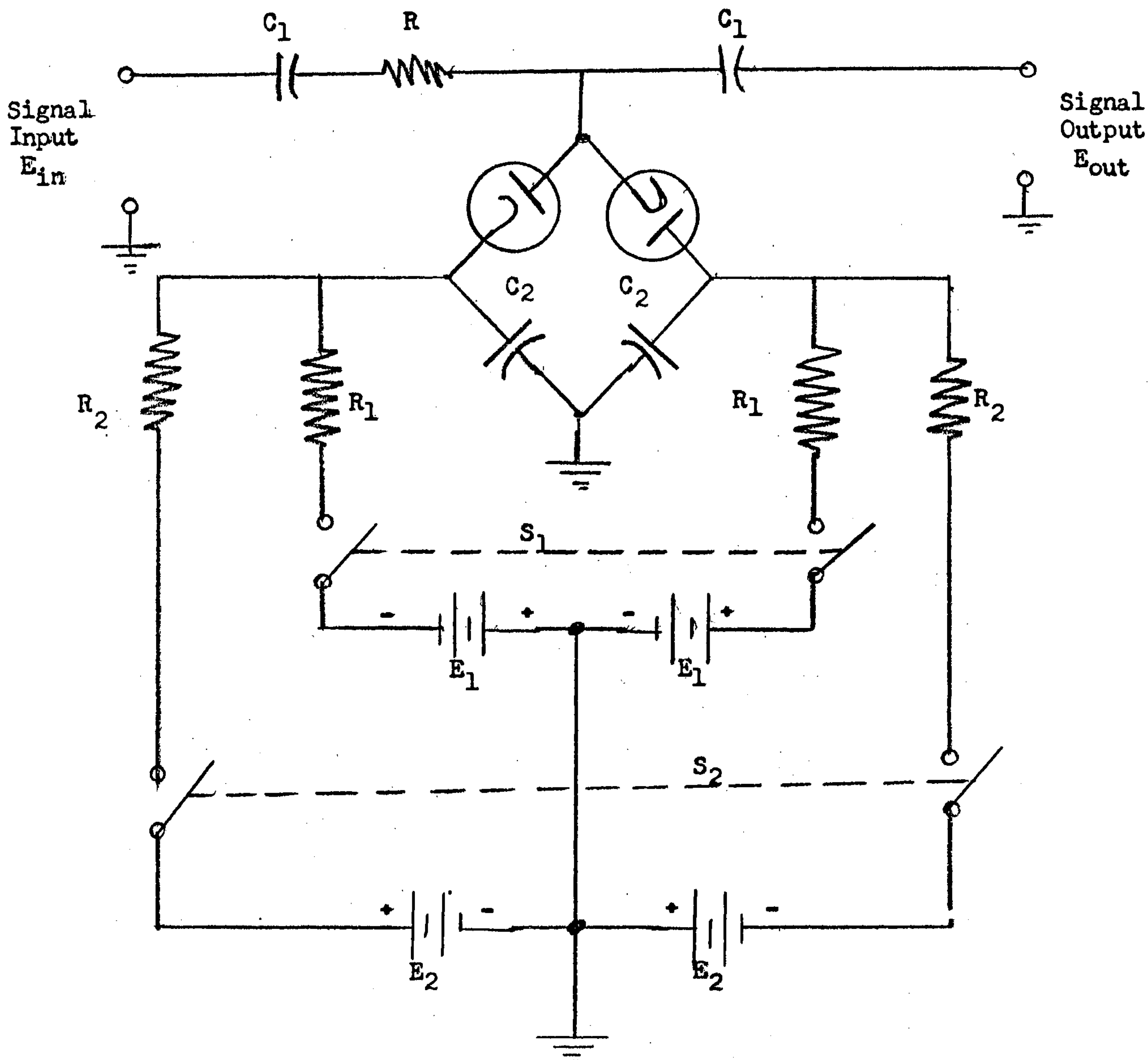

FIGURE 3

BASIC ATTENUATION CIRCUIT
WITH CONTROL CIRCUITRY

determined by the value of E_1 and R_1. E_1 and R_1 constitute a "constant current" circuit which implies that the current through the circuit is independent of the particular diodes in the circuit. This is accomplished by having E_1 many times larger than any normally encountered diode potentials. Since the initial attenuation condition is static, no current flows through the capacitors C_1 and C_2 after they are charged, and the current through the circuit will be

$$I = \frac{2E_1 + 2E_d}{2R_1}$$

where E_d represents normally encountered diode potentials.

and if $E_1 \gg E_d$, then

$$I = \frac{E_1}{R_1} \tag{7}$$

The attenuation of the circuit was shown in (6) to be

$$\text{Att (db)} = 20 \log\left(1 + \frac{R}{r_D}\right)$$

In (5), r_D was defined as equal to 1/2 r_{pl} and in (4) it was shown that r_p was equal to C/I. Substituting (4) into (5) into (6) yields

$$r_D = \frac{1}{2}\,\frac{C}{I}$$

$$\text{Att (db)} = 20 \log\left(1 + \frac{2IR}{C}\right)$$

and substituting I from (7),

$$\text{Att (db)} = 20 \log\left(1 + \frac{2E_1R}{CR_1}\right) \tag{8}$$

It should be noted that under the condition of initial attenuation, the capacitors C_2 are charged to a voltage which is equal to the voltage across the diodes. This voltage is a function of the variabilities of various diodes and will be different for each set of diodes used.

To operate the attenuator in the condition of expansion, switch S_1 is opened and switch S_2 is closed. As was stated previously, the diodes are operated in the exponential region of the plate-voltage/plate-current characteristic. Hence, if an incremental voltage, which is varying linearly with time is applied to a diode, then the diode current will vary exponentially with time. Since the plate resistance of a diode is proportional to the inverse of the diode current, then the plate resistance will vary exponentially with time. This is a desirable rate of change since the seismic signals likewise vary approximately exponentially with time. The circuit for generating the linearly varying voltage with time consists of E_2, R_2, and C_2. As in the circuitry which controlled the initial attenuation, E_2 and R_2 constitute a constant current source feeding the capacitors C_2. This is true if the voltage E_2 is large compared to the voltage on the capacitors. As was noted, the capacitors are initially charged to the potential of the diodes.

It is well known that for a capacitor $dE/dt = I/C$. Hence, if the current through the capacitors is constant, the incremental voltage across the capacitors per unit of time is constant and is proportional to the current through the capacitors. The current through the capacitors will, of course, be constant only if it is high compared to the current through the diodes and only for so long a period of time as the battery voltage E_2 is high compared to the voltage across the capacitors. The rate of rise of the voltage across the capacitors can be controlled by varying any of the parameters of the circuit: the battery voltage E_2, the resistance R_2, or the capacitors C_2. Circuit design can allow the plate resistance of the diodes to become extremely high compared to the dropping resistance R before the capacitors charge to such a voltage that their rise is no longer linear.

DEVELOPMENT OF ATTENUATION EQUATION

In the preceding section, the initial attenuation of the circuit was developed and the method by which a controllable rate of expansion is obtained was described. These two attenuation factors can be combined to produce attenuation curves which can be used for any combination of expansion rate and initial attenuation. These curves are very useful in field work and provide a nomograph for quick attenuation calculations.

In (4) it was shown that the resistance r_p of a single diode was equal to C/I. Taking the logarithms of this,

$$\ln r_p = \ln C - \ln I \tag{9}$$

Now, substituting (3) into (9),

$$\ln r_p = \ln C - A + BV \tag{10}$$

In the expansion circuit, the voltage across the capacitors C_2 and the diodes vary linearly with time and can be represented at any time t by the equation

$$V = V_o + Dt \tag{11}$$

where

V_o = diode voltage due to initial attenuation condition

D = rate of voltage rise across C_2

$$= \frac{E_2}{R_2} \cdot \frac{1}{C_2}$$

So, substituting for V from (11) into (10)

$$\ln r_p = \ln C - A + BV_o + BDt \tag{12}$$

By definition, the initial attenuation condition exists at t = o, and at this time $r_p = r_o$, so

$$\ln r_o = \ln C - A + BV_o$$

or

$$\ln C = \ln r_o + A - BV_o \tag{13}$$

Substituting (13) into (12)

$$\ln r_p = \ln r_o + BDt \tag{14}$$

and if we let $BD = q$

then $r_p = r_o \epsilon^{qt}$ (15)

From (4), at t = o

$$r_o = \frac{C}{I_o} \tag{16}$$

But, by substituting (16) into (15)

$$r_p = \frac{C}{I_o} \epsilon^{qt} \tag{17}$$

At the operating temperature of most diodes, the value of C is 0.1, so equation (17) may be written as

$$r_p = \frac{.1}{I_o} \epsilon^{qt} \tag{18}$$

and at t = o, $r_o = \frac{.1}{I_o}$ (19)

In equation (5) the shunt arm of the attenuator was R_D which was 1/2 the plate resistance of a single diode. Hence, from (18) and (5)

$$r_D = \frac{1}{2} r_p = \frac{.05}{I_o} \epsilon^{qt} \tag{20}$$

Substituting (20) into (6)

$$\text{Att (db)} = 20 \log \left(1 + \frac{R I_o}{.05 \epsilon^{qt}}\right)$$

$$\text{Att (db)} = 20 \log \left(1 + 20 R I_o \epsilon^{-qt}\right) \tag{21}$$

The value of I_o determines the initial attenuation, and the value of q determines the rate of expansion.

If we let I_o^{max} represent the largest practical value for the initial diode current I_o and I_o' represent an initial value of diode current which is less, and the attenuation for these conditions be Att (db)', then

$$\text{Att (db)}' = 20 \log \left(1 + 20 R I_o' \epsilon^{-qt}\right) \tag{22}$$

Also, from (15) $r_p = r_o \epsilon^{qt}$

and if r_o' and r_o^{max} are the plate resistances at I_o' and I_o^{max} respectively, then

$$r_o' = r_o^{max} \epsilon^{qt'}, \quad \text{or} \quad r_o^{max} = r_o' \epsilon^{-qt'}$$

and from (4)

$$r_o^{max} = \frac{C}{I_o^{max}} \quad \text{and} \quad r_o' = \frac{C}{I_o'}$$

therefore,

$$\frac{C}{I_o^{max}} = \frac{C}{I_o'} \epsilon^{-qt'}, \text{ or } \quad I_o' = I_o^{max} \epsilon^{-qt'} \tag{23}$$

Now, substituting (23) in (22),

$$Att(db)' = 20 \log(1 + 20 R I_o^{max} \epsilon^{-q(t+t')}) \tag{24}$$

An expansion with any initial attenuation (any I_o) may be described by the curve which begins with I_o^{max} by simply adding a constant t' to the time t in the equation. Similarly, it can be seen that this same curve may be used for different values of q(expansion rate) by multiplying t by the proper constant factor.

A single curve then could be used for any combination of expansion rate (q factor) and initial attenuation (I_o factor). However, in the practical application of this circuit, it is desirable to provide a set of curves for various specific values of q so as to avoid the complexity of multiplying the time scale by the proper factor. The construction of these curves is considered in the succeeding chapter.

CHAPTER THREE

CIRCUIT DESIGN AND RESULTS

In chapter three, the basic attenuation circuit and its control circuitry were described with little consideration as to the specific design problem. In this chapter, the practical design requirements are discussed with regard to signal frequencies to be passed, reliability of the initial attenuation, and rates of expansion desired. Practical results of the final circuit are also given.

The circuit which was finally used is shown in Figure 4. It is identical to the basic theoretical diagram shown in Figure 3 except that (1) a resistor to ground has been placed in the output lead to provide a grid return for the subsequent vacuum tube amplifier, (2) the method of providing the control voltages E_1 and E_2 is shown, and (3) a bias battery has been added in series with the diodes.

In normal operation, the "Initial Attenuation" and "Expansion Rate" controls are set by the operator to the desired values. These controls are stepped in discrete values so that the operator can return the settings to a particular point. At the moment the first seismic signals arrive after the dynamite detonation, the relay Ry is closed by means of auxiliary circuit apparatus and the initial attenuation circuit is disabled and the expansion circuit is brought into operation.

One of the fundamental requirements of the expansion circuit is that it operate satisfactorily at signal frequencies in the vicinity of 5 cps, and, further, that it introduce no more than 5 degree of phase shift at this frequency. The initial attenuation range required is from

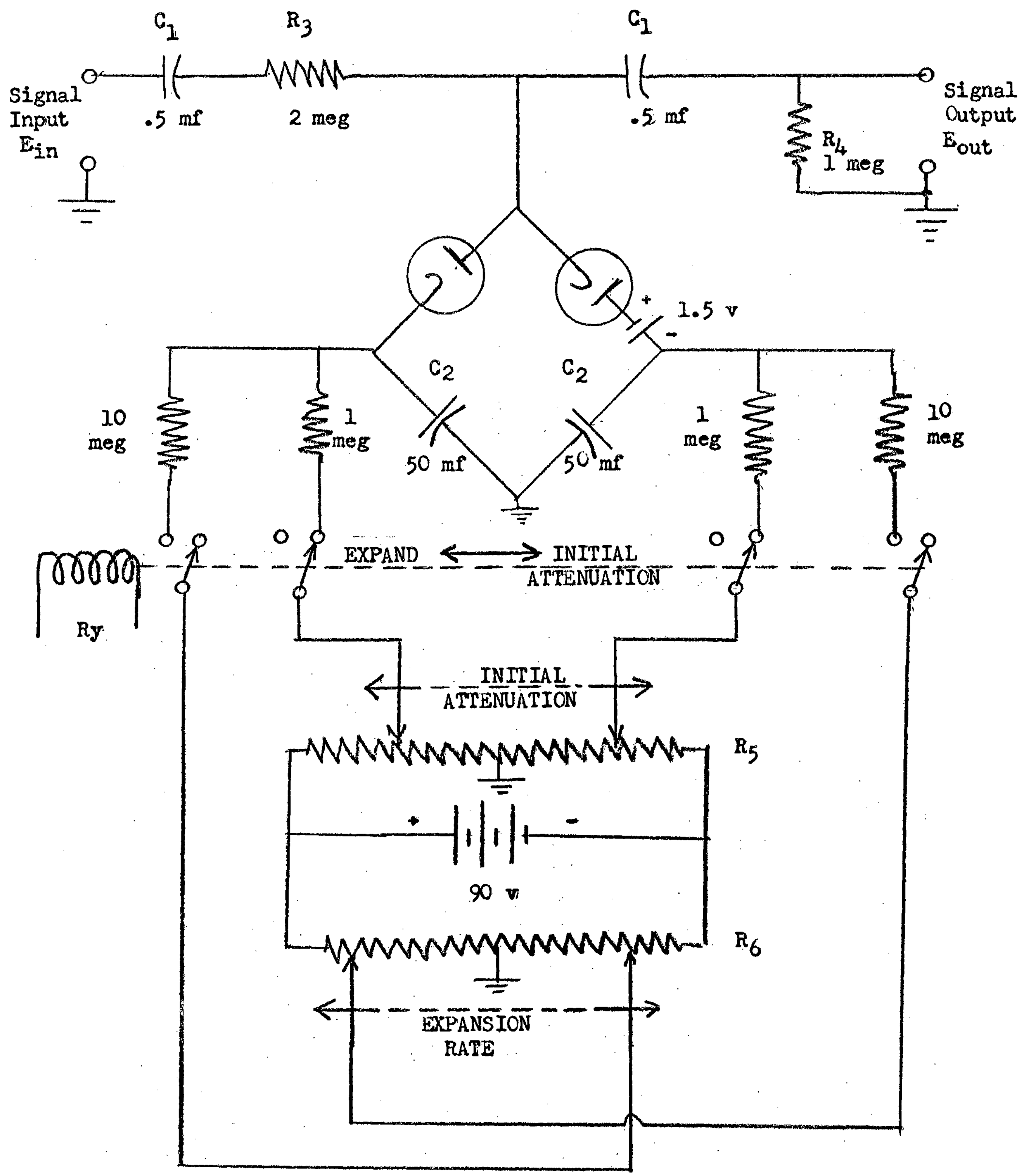

FIGURE 4 PRACTICAL ATTENUATION CIRCUIT

approximately 18 db to 40 db and should be resettable with an accuracy of plus or minus 1 db. The expansion rate range required is from approximately 50 db per second to 10 db per second, and should follow the theoretical curve within plus or minus 1 db.

The first design requirement is to determine the values of C_1 and C_2 with regard to the low frequency signal requirements. Since the phase shift requirements are much more severe than the amplitude response requirements, the phase shift only of the attenuator will be considered. Figure 5 is an equivalent circuit of the attenuator circuit which omits the control circuitry and combines the diode bridge circuit into an equivalent RC series network. When the diode resistance, R_D, is infinite, the phase shift of network is

$$\theta = \tan^{-1} \frac{1}{\omega (R_3 + R_4) C_1/2}$$

which equals 2.5 degrees at 5 cps for the values shown.

The minimum individual diode resistance that can consistently be obtained with commercial diodes in the initial velocity region is in the vicinity of 10,000 ohms. From (20) it can be see that r_D is 1/2 this value, or approximately 5,000 ohms, and the phase shift of the network due to C_2 is

$$\theta = \tan^{-1} \frac{1}{2C_2 \omega r_D}$$

which equals 3.7 degrees at 5 cps for the values shown. Since C_2 must be so large, this precludes the use of other than electrolytic capacitors, which are noted for relatively low leakage resistance. This is a rather serious handicap since the stability of the circuit in the initial attenuation condition relies on the condition that all of the initial attenuation current flow through the

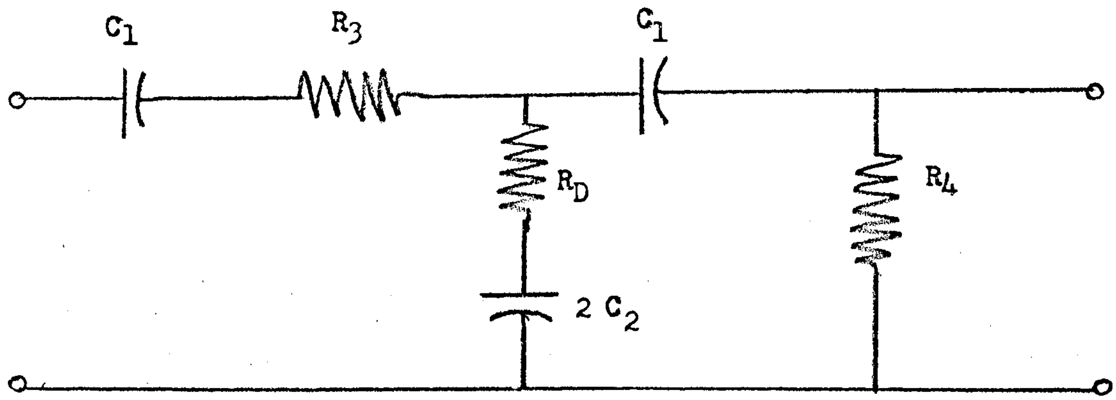

FIGURE 5 EQUIVALENT ATTENUATION CIRCUIT

diodes and not through the associated capacitors. For this reason, it was expected that at low initial attenuation settings (small I_o) there would be some error due to the diode current and capacitance leakage current being comparable in value. Test data confirmed this, but indicated that a second source of error at low initial attenuation settings was even more serious.

This second source of trouble was the difficulty in providing a constant current source to the diodes in the initial attenuation condition at low attenuation levels. Field experience has indicated that resistors larger than 10 megohms are not very stable, which requires that the initial attenuation voltage be comparable to the diode voltage at low attenuation levels. This problem was solved by inserting the 1.5 volt battery in series with the diodes to partially cancel out the average emission voltage. This in turn further reduced the voltage across the electrolytic capacitors and caused their leakage to be lower. Tests were made with and without the bias battery in the circuit with both typical low and high diodes and the data are presented in the table below.

		Attenuation (db) No Bias		Attenuation (db) 1.5 V. Bias	
E	Calculated Attenuation (db)	Low Diode	High Diode	Low Diode	High Diode
5.0	17.6	23	24	16	19
10.0	23.1	26	28	23	24
20.0	28.8	31	32	29	29
40.0	34.5	36	36	35.5	35
90.0	41.6	42	42	42	42

A peculiar phenomenon was noted concerning the characteristic of the electrolytic capacitors used in this circuit. The capacity was carefully measured at 50 cps, and from this figure the incremental voltage per unit of current per unit of time was calculated using the formula $dE/dt = I/C$. In every case, the incremental voltage would indicate that the capacitance was approximately 20% higher than measured at 50 cps. This could not be accounted for either by dc leakage or by power factor measurements. However, power factor measurements could not be made at extremely low frequencies (i.e., below 10 cps), so it remains quite probable that, instead of the capacitor having an effective increase in capacitance, part of the current is being diverted to polarization of the capacitor, thus causing the voltage rise time to increase. This could erroneously lead to the assumption that the effective capacitance had increased; although for all practical purposes in this application, the increased values of capacitance must be used for calculations involving the expansion rate. It is believed that this effect is due to some predictable physical phenomena because the characteristic noted was remarkably consistent in a large group of capacitors.

A plot of the theoretical attenuation curves as a function of time for the circuit of Figure 4 is shown in Figure 6. These theoretical attenuation curves were determined from formula (21). The value of R substituted in formula (21) is .67 megohms. This value was obtained from the parallel resistance of R_3 and R_4 in Figure 4. This substitution makes use of Thevenin's theorem.

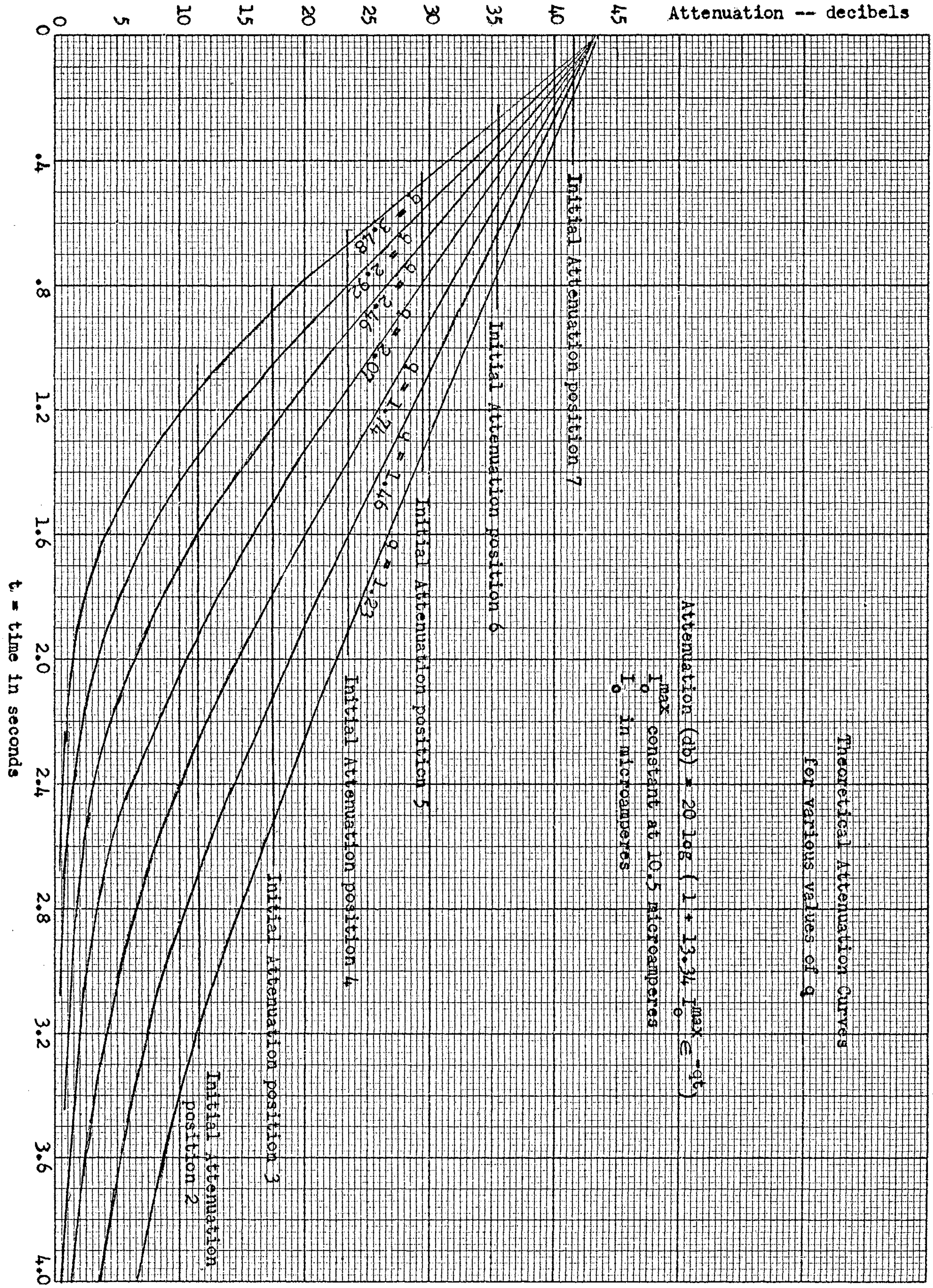

FIGURE 6 THEORETICAL ATTENUATION CURVES

Several attenuation curves are shown for specific values of q. These particular values of q shown are obtained by the various settings of the "expansion rate" control shown in Figure 4. Also shown are several specific values of initial attenuation. These particular values are obtained by the various settings of the "initial attenuation" control shown in Figure 4. It was shown in formula (24) that an expansion with any initial attenuation can be described by the curve which begins with I_o^{max} by simply adding a constant t' to the time t in the equation. Thus a change in initial attenuation can be represented by a shift in the zero of the time axis.

To illustrate the use of these curves, an example will be shown. Suppose that the initial attenuation control is set to position 6 and the expansion rate control set to give a value of q = 1.74. Then the initial attenuation will be at the intersection of the q = 1.74 curve and the initial attenuation position 6 line, which is 35.5 db. This point occurs at .54 seconds on the time scale. However, the initial attenuation occurs at t = 0 by definition. Hence, the time scale must be shifted to the right by .54 seconds. Now assume that it is desired to determine the attenuation at a time one second after the expander has started operating. To account for the shift in the time scale, .54 seconds must be added to the time desired of one second, or 1.54 seconds. The intersection of the q = 1.74 curve and 1.54 seconds gives 21 db attenuation which is the attenuation obtained for an expansion period of 1 second under the condition stated.

The curves shown in Figure 6 have been checked frequently over a period of several years operation of the circuit in the field. A maximum error of plus or minus 1 db has been maintained consistently, both for the initial attenuation and the attenuation during the expansion period.

Maintenance problems on the attenuation circuit and its associated control circuitry have been minor. An occasional expansion time constant electrolytic capacitor has dried out, causing the expansion rate to change. This is usually evidenced in operation by observing that the expansion control voltage is introduced in the signal path due to the unbalance of the attenuation bridge. This causes a slow apparent d-c drift of the oscillographic record trace having the defective component. Defective capacitors have been replaced by sintered tantalum electrolytic capacitors which are hermetically sealed in a solid silver case. These capacitors are not unduly expensive and have exceptionally low leakage current and long life. The other maintenance problem consists of the thermionic diodes becoming very slightly gassy. A diode which has become gassy does not follow the plate voltage initial electron velocity plate current characteristic described in Chapter Two when the plate current is very low. The symptoms on the oscillograph record are approximately the same as those due to a defective capacitor.

CHAPTER FOUR

SUMMARY AND CONCLUSIONS

In this thesis a new method for reliably controlling the gain of a seismograph amplifier is presented. The gain control is called an expander and causes the gain or sensitivity of the amplifier to increase as a function of time after the first large amplitude reflection signals are received. Functionally, this is necessary because succeeding reflection signals come from greater depths and progressively become weaker. To successfully observe these subsequent signals, the sensitivity of the amplifier must be increased to produce a useable amplitude signal.

When doing basic research on the strength of seismic signals, it is desirable to know the sensitivity of the amplifier as a function of time. Knowing the time of any particular seismic event, its particular amplitude on the oscillographic record, and the sensitivity of the amplifier, its amplitude can be computed.

The circuit is also useful when recording seismic signals of a very low frequency, because any automatic means of gain adjustment is apt to distort the low frequency signals. This is particularly useful when recording seismic signals magnetically where full fidelity must be maintained.

Previous expander circuits have been developed but have been generally unsatisfactory because of the variations in tube characteristics. The circuit described herein was developed to provide stable attenuation and expansion characteristics regardless of the common variations in vacuum tubes. The principle upon which it is based utilizes the exponential portion of the plate-voltage/plate-current characteristic of a thermionic diode. It is shown, for all practical purposes, that the plate resistance of such a diode in the electron initial velocity region is equal to .1 divided by its plate current.

This characteristic is utilized in a bridge type attenuator which prevents the control voltage to the diode from entering the signal path. The control circuitry is developed which will cause this attenuator to attenuate by a predictable and consistent amount, in order to properly receive the large amplitude first arrival seismic signals. The circuitry will also cause this attenuation to vary at a predictable and consistent rate which can be adjusted by an operator in order to satisfactorily receive the subsequent weaker signals.

The circuit was installed in field equipment and has been in use for several years. Periodic calibration checks have been made and indicate that it is accurate to within 1 db of the theoretical values. Maintenance problems are minor and the diodes do not have to be selected for use in the circuit. These data prove that the circuit theory is not only correct, but that the design is practical from the operational standpoint of view.

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